

UNCONVENTIONAL OIL & GAS REPORT™

Understanding the science behind induced seismicity

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For several decades in the US, earthquakes occurred at a steady rate of 21 events per year. Beginning in 2001, this rate began to increase and peaked in 2011 at 188 earthquakes.

Impoundment of reservoirs, surface and underground mining; withdrawal of fluids and gas from the subsurface; and injection of fluids into underground formations are capable of inducing earthquakes, according to research conducted by William Ellsworth, seismologist for the US Geological Survey (USGS) Earthquake Science Center. Ellsworth recently published his findings in *Science*, the academic journal of the American Association for the Advancement of Science. Disposal wells could be a source for some of the increase in earthquakes throughout the US Midcontinent, according to Ellsworth.

New drilling and well completion technologies have enabled the extraction of oil and gas from previously unproductive formations. In some regions, this new production also has increased the amount of fluid being disposed of in deep injection wells.

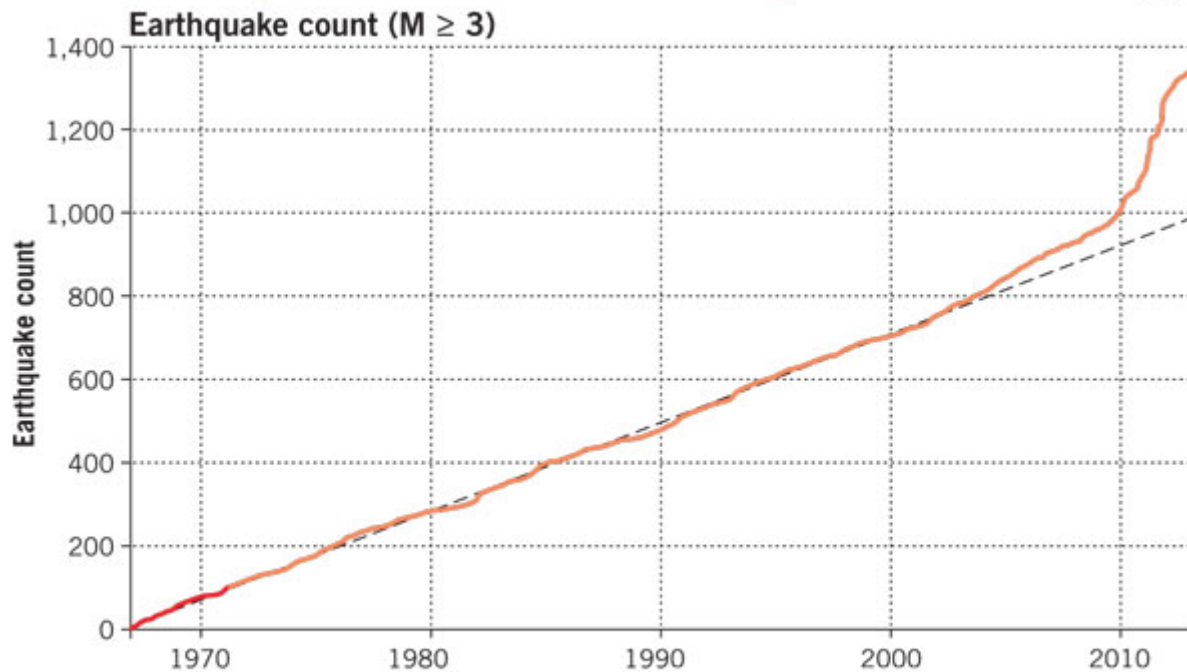
Degrees of magnitude

Hydraulic fracturing essentially functions through the creation of microearthquakes (those with magnitudes [Mw] below 2.0). "The actual fracing process has very low risk associated with it," Ellsworth said. "Different lines of evidence show that fracing is an unlikely source for a large earthquake."

In the US, more than 100,000 wells have been completed using hydraulic fracturing in recent years. To date, the largest induced earthquake from this process was Mw 3.6. According to the findings, this is too small to pose a serious risk to the community. The study claims that higher risks are posed by wastewater disposal by injection into deep wells. This process has the potential to induce larger earthquakes that could have a greater impact.

EARTHQUAKES (US MIDCONTINENT 1967-2012)

FIG. 1



Source: Earthquake Science Center, USGS

Earthquakes with magnitude ($M \geq 3$) in the US Midcontinent, 1967–2012.

An analysis of earthquakes and wastewater wells by geophysicist Cliff Frohlich of the University of Texas at Austin (UT) found spatial associations between high-magnitude earthquakes and high-volume injection wells. Risk factors identified in USGS research are the combination of deep disposal wells that inject into rocks that may be in communication with the crystalline basement and high-volume injection combined with high pressure. "These are all factors that seem to be common among the wells where problems have occurred," Ellsworth said.

In 2011 and 2012, disposal wells may have triggered several of the largest earthquakes in the Midcontinent. The largest of these was a Mw 5.6 event that occurred in central Oklahoma. According to a study by geophysicist Katie Keranen of the University of Oklahoma, injection carried out at a nearby disposal well weakened a preexisting fault by elevating the fluid pressure in the formation.

Formation factors

Factors that can induce earthquakes are stresses in the ground—differential and sheer—and a fault that could move under the applied stresses. "The stresses are high virtually everywhere. That is a consequence of the nature of the planet we live on," Ellsworth said. "Even though the Midcontinent is not an area that is actively deforming today, the stresses are present, and in many places they are close to the failure point," he added. Given that a fault has the proper orientation within the current stress field, an earthquake can occur.

However, only a small fraction of disposal wells have earthquake potential, according to Ellsworth. In the US there are more than 30,000 wastewater disposal wells. The problematic wells typically dispose of very large volumes of water and communicate pressure perturbations directly into basement faults.

One lesson to be drawn from the infrequent association of wastewater wells and earthquakes is that in most cases the formations selected for disposal seem to be appropriate. "The environmental regulations for injection wells are primarily designed to protect freshwater aquifers from pollution," Ellsworth explained. "Where there are problems, we have seen evidence that the pressures have communicated with faults at greater depths."

The crystalline basement is known to have an abundance of faults, and imaging faults within this formation is difficult. "An assumption can be made that there is likely going to be a fault that could slip if the pressure from injection is capable of communicating with that fault. That's the thing you want to avoid," Ellsworth said.

On Dec. 31, 2011, Youngstown, Ohio, experienced an earthquake (Mw 4), which caused only minor damage in some areas. In this case, fluid was being injected into a well that was at the very base of the sedimentary column that also penetrated into the basement. "The fault that slipped was in the basement a bit deeper than the disposal well," Ellsworth said.

Data limitations

Quantifying seismic hazards associated with injection-induced earthquakes, such as those that struck in 2011, presents difficult challenges that will require new research into the physics of induced earthquakes and the potential for inducing large-magnitude events.

Most of the wastewater wells in the US do not have any detected seismicity associated with them. The current level of earthquake detection means that the potential is not high everywhere disposal wells are located. "The larger question that we are facing is trying to understand the conditions at the wells that are problematic," Ellsworth said. "Ultimately, we would like to know more about the state of stress underground before injection begins and what the natural formations were, along with pressures and how these pressures have varied over time."

Historically, reporting injection well data is done annually by the operators of disposal wells. Most are required only to report monthly average pressures. "That's useful to have, but it's not ideal from the standpoint of monitoring," Ellsworth said. Data gathering on a national basis can be difficult. "Some states have well-maintained databases and there are good reasons to trust those numbers. In other states the situation can be less clear," Ellsworth said.

"There is no revenue coming out of this part of the industry as opposed to production, so it's not surprising that those records in some states are not in as great a shape as they might be for this purpose," he continued. In many cases, obtaining a simple list of what the wells are and how much water was injected over a period of time is not straightforward. "It's something that we are currently working on, but we do not have a national snapshot at this point," he said.

From a geomechanical standpoint, total fluid injected and pressures are key findings to perform proper reservoir modeling. Ellsworth said understanding how high pressures may be and where these pressures may be transmitted are important factors in early prediction of seismic events.

Wastewater comes from many sources, and it is not solely derived from flowback or coproduction water from shale gas. The oil and gas industry will need clear requirements for operation, and regulators must have a solid scientific basis for those requirements.

Rules of disposal

Produced water from aging wells supply a large portion of the wastewater currently disposed through deep injection wells. Modern advances in recycling and reuse in unconventional operations have netted a certain decrease in the amount of flowback and coproduced water being disposed.

"Where water can be treated it becomes a valuable resource," Ellsworth said.

In some cases, injection is necessary. Wastewater wells are permitted without consideration of earthquake hazard issues. "They are governed by old laws related to drinking water, and that is very important," Ellsworth said. However, as the science improves, new rules may be created that require more data to avoid communication with existing faults. The US Environmental Protection Agency has considered revising its guidelines to include earthquake hazards, but this has been a very slow process and will take time.

"The recent increase from 2011 is not all related to fracking, that is clear," Ellsworth said. "The frustrating part is that for some of the areas that contribute heavily to the increase, such as central Oklahoma, we do not have clear answers as to why," he added. The region is home to many different activities including unconventional development and enhanced recovery. Sometimes, the source of earthquake events is clearly identifiable. "In Arkansas, we can trace the increase in seismic events to particular disposal wells, and attribute the earthquakes that were induced to them," Ellsworth said.

In areas like the Cogdell and North Snider oil fields in West Texas, earthquakes can accompany secondary recovery activity. "It's been known for some time that earthquakes can be induced in these fields," Ellsworth said.

Managing risks

Because current regulatory standards revolve around protecting potable water sources, timely reporting of injection volumes and pressures is lacking in many instances.

According to Ellsworth's findings, the situation is far from ideal for managing earthquake risk from injection activities. Seismic monitoring capabilities also are limited in many areas where wastewater injection has increased, which can prevent the timely detection of small earthquakes that often presage larger seismic events.

"One of the methods that has been widely discussed is the 'traffic light' system, which could help manage earthquake risks," he said. Setting seismic activity thresholds that prompt a reduction in injection rate or pressure is an effective method to manage high-magnitude earthquake risks. Such

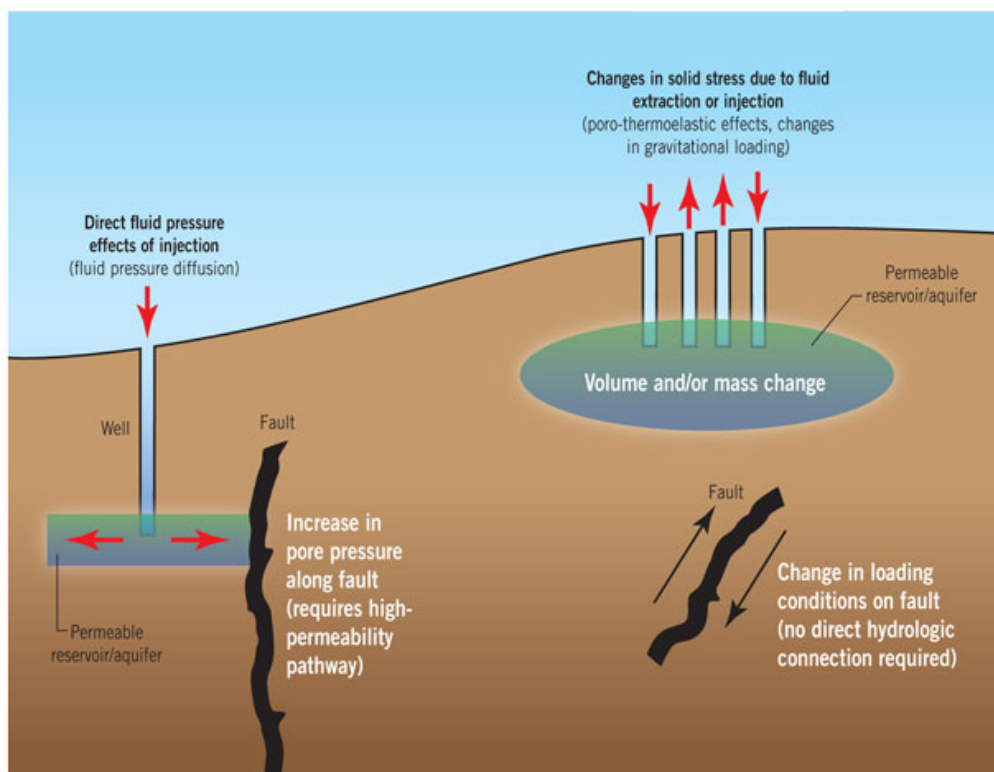
systems have been used selectively since the late 1960s. And, in the case of the Youngstown earthquake in 2011, the decision to stop injection in the associated disposal well was based on seismicity from the day before, and seismicity near the well declined within a month.

All of the examples for effective management feature better seismic monitoring capabilities than currently exist throughout the US. Ellsworth's findings show that lowering the magnitude detection threshold in regions where injection wells are concentrated to below Mw 2.0 would increase the effectiveness of the traffic light system as the current US detection threshold of Mw 3.0 in many of these areas would have a limited value.

"We need better reporting of information on wastewater disposal than is currently available," Ellsworth said. Improvements in the timeliness of reporting injection data to regulatory agencies could provide usable information on hydrologic conditions potentially associated with induced seismicity. Specific data such as volumes and injection pressures reported on a daily basis could provide better management of risks. "We would need improved seismic monitoring so that the indications of problems that are often seen in smaller earthquakes would be detected in a timely manner," Ellsworth reiterated.

MECHANISMS FOR INDUCING EARTHQUAKES

FIG. 2



Schematic diagram of mechanisms for inducing earthquakes

Ultimately, better knowledge of the subsurface near disposal well locations is needed to develop a predictive understanding of the hazards posed by induced earthquakes.

Because earthquakes are predominantly natural occurrences, it can be extremely difficult to identify sources of inducement in some cases. In Ohio and Arkansas, disposal wells were identified as a direct cause, but in most cases there is no clear definition of a single source.

Increased earthquake occurrence in the Midcontinent will require more research, but there have been international examples of induced seismicity.

Since 1900, the Netherlands has experienced almost 50 earthquakes of Mw 3.0 or higher. The majority of these seismic events have occurred in the southern part of the country as a result of natural causes. The Dutch government has conceded that virtually all of the earthquakes in the northern part of the Netherlands are due to gas production. Changes in rock strata as gas is produced have led to an increase in earthquakes in the region, causing minor damage to many homes. To date, the most severe earthquake induced by gas production registered Mw 3.5.

Gas production in the country's Groningen region—an area that contains up to 1,800 natural faults in the porous Rotliegend sandstone subsurface—is undergoing slow, natural subsidence. The area has been a major natural gas resource in the country since 1963, and as a result of 50 years of depletion, the ground surface above the center of the Groningen field has subsided by more than 25 cm (9.84 in.).

As early as 2003, the Netherlands has enacted provisions within its Mining Act that require a portion of the revenues from gas production be diverted into a Damage Guarantee Fund from which citizens who have incurred damage from induced earthquakes could qualify for reimbursements. To date, the fund contains €100 million.

More research is being carried out by USGS and several leading universities, including Stanford, UT, and the University of Oklahoma (OU). "We've also seen some interest from several operating companies," Ellsworth said.

Industry involvement

Operating companies are taking precautions whenever possible to prevent triggering seismicity. "While specific cases are still open to debate, there is an emerging scientific consensus that, out of 30,000 disposal wells in the US, cases are rare where seismic events have been triggered," said Randy Keller, director of the Oklahoma Geological Survey (OGS) and Edward Lamb McCollough Chair in Geology and Geophysics at OU. Keller also believes that the industry recognizes the risks and is currently taking action to develop techniques for mitigating further earthquakes.

OGS recently convened a workshop (July 16, 2013) as a first step toward developing a set of recommended best practices to address the issue of induced/triggered seismicity. According to Keller, about 70 participants (the majority being from industry) shared ideas and experiences during a series of technical talks and in breakout sessions. Follow-up meetings and a report will be forthcoming.

"There are numerous cases where oil and gas companies are conducting internal research, and some companies have been very open in discussing this issue and have sought input from the scientific community," Keller said. While funding remains a challenge for external, neutral research groups, the dialogue about the wider issue has grown within the industry, according to Keller.

"A broad cross-section of the petroleum industry realizes that the issue of triggered or induced earthquakes can no longer be ignored," Keller said.

See original article online at <http://www.ogj.com/articles/uogr/print/volume-1/issue-3/understanding-the-science-behind-induced-seismicity.html>